# Finite Element Modeling of Anisotropic Properties of Cu-Ag Metal Matrix Composites

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***Abstract*—This research investigated the sensitivity of the mean phase strains in a heavily drawn copper-silver fiber composite to the inherent mechanical anisotropies resulting from the texture produced by the drawing process. The work performed here is a precursor to the neutron diffraction experiments to be performed to advance the understanding of the residual stress development during the fabrication process and how these residual strains change as a function of loading. Copper-Silver (Cu-Ag) metal matrix composites are used as high strength conductors for high performance pulse magnets. To produce the filamentary nature and extreme work hardening a cold-working co-deformation fabrication process is used which in turn induces crystallographic alignment of Ag fibers and Cu matrix. In the limiting case the material behavior is close to single-crystalline Ag fibers embedded in single-crystalline Cu matrix. Since this means that the mechanical elastic properties will be strongly anisotropic we investigated the sensitivity of the mean phase strains to the degree of anisotropy using a three-dimensional finite element model. The anisotropic elastic properties of the Ag and Cu were incorporated. Several different loading conditions were applied. Results of the various loading conditions were then used to obtain an estimate of the mean phase strains of the composite.**

## I. INTRODUCTION

In the last decade the achievable magnetic field in high field magnets have increased significantly, and one of the restraining factors for their application is the limited strength of the coil material used for the magnet. For higher magnetic fields some reinforcement is needed for the coil wire. As a coil material, compared to the unreinforced matrix Metal Matrix Composites (MMCs) provide more desirable thermal and mechanical properties such as stiffness and coefficient of thermal expansion (CTE). When ductile two-phase alloys are heavily deformed, the resulting structure's strength typically is much greater than the strength predicted on a mixture basis from the cold working of the individual phases. One such material, Copper-Silver metal matrix composite will be investigated in this work.

As a preliminary study, we have investigated the effect of the anisotropic material parameters compared to the isotropic case using finite element (FE) modeling.

Manuscript received October 15, 1999

This work was funded in part by a New Mexico Universities Collaborative Research (NUCOR) grant from the Los Alamos National Laboratory, Los Alamos, New Mexico.

## II. MATERIAL

One of the most successful coil materials, so far, is the highly deformed copper/silver composite [1]. In addition to high strength and high conductivity this composite posses good workability and can be formed into a desirable final cross-section. The manufacturing process includes forging, annealing and cold drawing. The final cross-section of the wire is 5.2 mm × 8.6 mm × 1.6 mm.

The copper/silver composite has been co-deformed to high strains, up to 600% [2], and therefore have a pronounced texture. Due to the elastic anisotropy of the materials and the texture both materials have anisotropic macroscopic stiffness.

## III. MODELING

The mesh in Fig. 1 was generated using the commercial code I-DEAS™ [3]. In order to include the anisotropy of the materials, a full 3-Dimensional mesh was used. The model consists of a cylindrical Ag fiber embedded in a rectangular Cu matrix with quarter symmetry and second order elements. The model has an aspect ratio of 5 in the axial direction of the fiber. An increased mesh density was used near the matrix/fiber interface to better capture the high stress concentration near the interface. In this model the composition of Ag is 24% of the total weight.

The finite element calculations were done using the commercial code ABAQUS™ [4].The material parameters used in the calculations are given in Table I. The macroscopic stiffness was calculated from the single crystal stiffness using a Kröner [5] type self-consistent model [6]. In the isotropic case, a set of 1000 randomly orientated grains were used in the calculations, and in the orthotropic case all the grains have the <111> lattice plane normal along the macroscopic $x_3$ axis, along the fiber axis, and then randomly rotated around this axis. This representation of a fiber texture, the orthotropic case, is the limiting case for an infinite strong <111> texture. The plastic behavior of the two materials is given as a tabulated set of plastic strains at a given stress values (Von Mises stress). The relationship between plastic strain and stress was interpolated linearly between the values given in Table I.

Normal symmetry assumptions were used for the three planes $x_1 = 0$, $x_2 = 0$ and $x_3 = 0$. The other two surfaces along the fibers ($x_1$ = const. and $x_2$ = const.) were constrained to remain planar to assure assumptions of symmetry.

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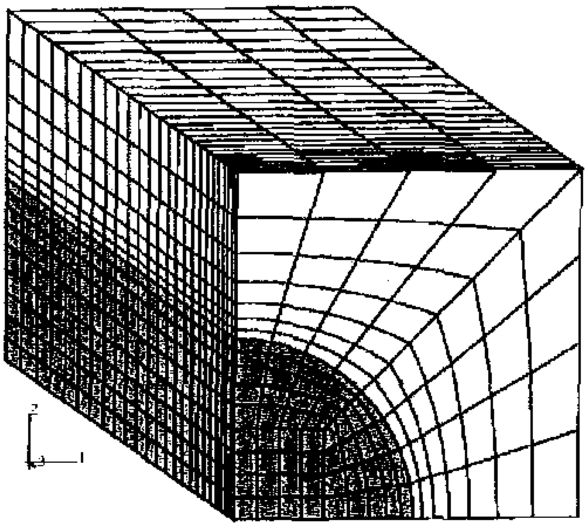


Fig. 1. Finite element mesh. Note that the dark quarter circle represents the Ag fiber.

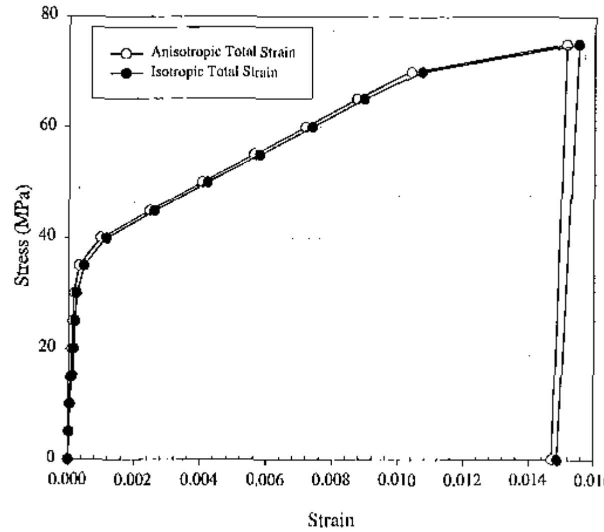


Fig. 2. Total strains for isotropic and anisotropic material properties.

The load was applied as a surface load on the free end of the mesh ($x_3$ = const.), which was allowed to deform freely (at increments of 5 MPa to a maximum of 75 MPa and then unloaded in a single step).

In the calculations we have used the microstructure of the heavily deformed composite, a continuous fiber in a matrix, but as the yield stress and plastic behavior at this stage are unknown, we have used generic material parameters for annealed materials. The macroscopic stress-strain curve is shown in Fig. 2.

## IV. Results and Discussion

To compare the FE and experimental (neutron) results at a future date, the strains were averaged over the phase volumes of the composite. As seen in Fig. 2, the difference in macroscopic behavior between the isotropic case and the orthotropic case is relatively small. Both predictions show a total strain of about 1.5% at a maximum load of 75 MPa.

It is our goal to validate the FE predictions using neutron diffraction measurements of internal lattice strain in the composite. Hence, we have to compare the development of the *elastic* strain in the phases, as diffraction techniques only measure the *elastic* component of the strain. Fig. 3 shows the applied stress versus the elastic strain for the two phases.

As seen from Fig. 3, the difference between the isotropic case and the orthotropic case is much more pronounced when we are only looking at the *elastic* strain component. From the kinks in the lines, we can deduce that the copper starts yielding first, above 30 MPa, as the copper curve deflects upwards. This indicates that load is transferred from copper to silver. When silver becomes plastic, above 40 MPa, we see that the load transfer back to copper again. Over most of the range the difference between the isotropic and orthotropic cases are larger than 100 $\mu\varepsilon$, and therefore will be distinguishable by neutron diffraction.

TABLE I
Material Parameters Used In The FE Calculations.

| | Copper | | | Silver | | |
|---|---|---|---|---|---|---|
| Single crystal stiffness | $C_{11}$ = | 168.4 | GPa | $C_{11}$ = | 124.0 | GPa |
| (Cu: [7], Ag: [8]) | $C_{12}$ = | 121.4 | GPa | $C_{12}$ = | 94.0 | GPa |
| | $C_{44}$ = | 75.4 | GPa | $C_{44}$ = | 46.5 | GPa |
| Calculated Young's modulus | | 129.1 | GPa | | 82.4 | GPa |
| Calculated Poisson's ratio | | 0.343 | | | 0.368 | |
| Calculated Orthotropic stiffness | $L_{11}$ = | 214.0 | GPa | $L_{11}$ = | 151.9 | GPa |
| | $L_{12}$ = | 110.4 | GPa | $L_{12}$ = | 87.1 | GPa |
| | $L_{13}$ = | 86.8 | GPa | $L_{13}$ = | 73.0 | GPa |
| | $L_{33}$ = | 237.6 | GPa | $L_{33}$ = | 166.0 | GPa |
| | $L_{44}$ = | 35.6 | GPa | $L_{44}$ = | 22.5 | GPa |
| Plastic behavior | Stress | Plastic strain | | Stress | Plastic strain | |
| (The stress value at 0.0% plastic strain correspond to the yield stress) | 33.0 MPa | 0.0 | % | 54.0 MPa | 0.0 | % |
| | 36.0 MPa | 0.1 | % | 60.0 MPa | 0.1 | % |
| | 65.0 MPa | 1.0 | % | 90.0 MPa | 1.0 | % |
| | 100.0 MPa | 5.0 | % | 150.0 MPa | 5.0 | % |

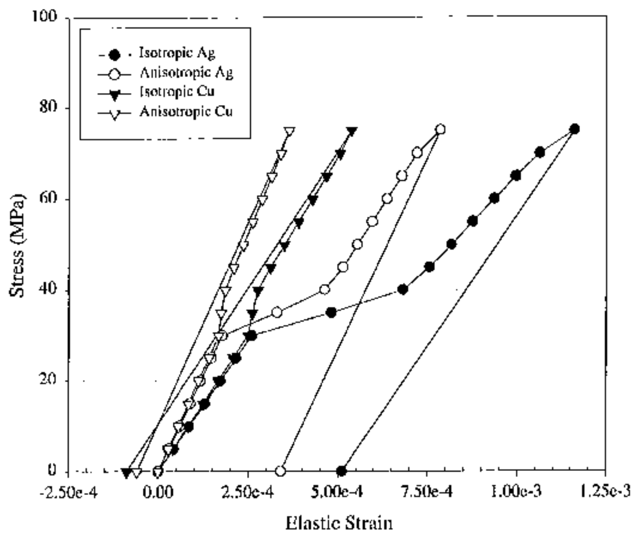


Fig. 3. Elastic strains for isotropic and anisotropic material properties.

## V. Conclusion

The design and application of new magnetic coil materials require the development of analytical methods capable of predicting their behavior under loading conditions typical of real applications. This research has been a first step towards that goal, and we have demonstrated that the difference between the development of elastic strains between the isotropic and orthotropic cases is large enough to be measured by neutron diffraction.

Finally, strains in the perpendicular direction to the fiber were not included and this should be addressed in the future. Also, we hope to incorporate thermal loads to this model in order to study thermal strains in this wire material.

## Acknowledgment

This work was funded in part by a New Mexico Universities Collaborative Research (NUCOR) grant from the Los Alamos National Laboratory, Los Alamos, New Mexico.

Also, this work was supported in part under the auspices of the United States Department of Energy. The Manuel Lujan Jr. Neutron Scattering Center is a national user facility funded by the United States Department of Energy, Office of Basic Energy Sciences – Material Science, under contract number W-7405-ENG-36 with the university of California.

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